Future Advanced Windows for Zero-Energy Homes

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ABSTRACT

Over the past 15 years, low-emissivity and other technological improvements have significantly improved the energy efficiency of windows sold in the United States. However, as interest increases in the concept of zero-energy homes—buildings that do not consume any nonrenewable or net energy from the utility grid—even today's highest-performance window products will not be sufficient. This simulation study compares today's typical residential windows, today's most efficient residential windows, and several options for advanced window technologies, including products with improved fixed or static properties and products with dynamic solar heat gain properties. Nine representative window products are examined in eight representative U.S. climates. Annual energy and peak demand impacts are investigated. We conclude that a new generation of window products is necessary for zero-energy homes if windows are not to be an energy drain on these homes. Windows with dynamic solar heat gain properties are found to offer significant potential in reducing energy use and peak demands in northern and central climates, while windows with very low (static) solar heat gain properties offer the most potential in southern climates.

INTRODUCTION

During the past 15 years, low-emissivity (low-e) glazings and other improvements in window technology have significantly reduced window-related energy use and peak demand in residential buildings. Estimates indicate that more than 40% of windows sold today have low-e coatings (Ducker 2000), and low-e products are expected to dominate the market in the near future. Despite the energy advantages of low-e coatings, windows still represent a significant energy liability in resi-

dential buildings. Approximately 2.7 quads (2.8 EJ; Appendix A) of the total 9.6 quads (10.1 EJ) of source energy used for residential heating and cooling is attributable to today's window stock. This amounts to nearly three percent of total U.S. energy consumption, or a cost of more than $25 billion (DOE 2002). If all windows in today's residential stock were low-e, the energy use attributable to windows would drop to an estimated 1.6 quads (1.7 EJ; Appendix B).

However, as interest increases in the concept of zero-energy homes—buildings that do not consume any nonrenewable or net energy from the utility grid—even today's highest-performance window products will not be able to meet the requirements of a zero-energy home. A new generation of highly efficient windows will require new technologies. As today's highly efficient ("super") windows tend to be climate-specific, one way to improve window energy efficiency would be to develop dynamic fenestration systems that can alter their solar heat gain properties according to seasonal/temperature variations. This paper describes a simulation study that compares the performance of currently available windows, future windows with dynamic solar heat gain properties, and future windows that represent only improvements in the static properties of today's highly efficient super windows. Performance was studied for different U.S. climates.

In order to understand the advantages of a dynamic window system, it is important to understand the limitations on the performance of current high-performance, low-e windows. Today's low-e windows are designed to address the parameters that are typically used to quantify energy performance: U-factor (a measure of the heat lost because of indoor-outdoor temperature differences) and solar heat gain coeffi-

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cient (SHGC, which quantifies the fraction of heat from incident solar radiation entering a space).

By reflecting long-wave radiant energy, low-e windows reduce window U-factors and therefore reduce heat loss through windows. Although valuable in all climates, reduced U-factors are most useful in colder climates where heating energy requirements, driven by large indoor-outdoor temperature differences, are significant.

Many low-e coatings are tuned to reflect the solar infrared (or invisible) portion of the sun's energy in order to reduce a window's SHGC. Such products, known as "low-gain" or "spectrally selective" glazings, are effective in climates where cooling dominates energy bills, but these products also reduce solar gain through windows during the heating season, thus reducing the windows' ability to provide free solar heat. Low U-factors combined with solar gains are important in turning windows from liabilities to assets during the heating season. Some low-e coatings (high-solar-gain, low-e) have been developed to maximize the SHGC; these products are optimal in climates where heating dominates the energy used for space conditioning because high solar gains can offset heating loads.

In short, currently available products represent a compromise: they perform best in climates where either heating or cooling is the dominant space-conditioning use, but not both. Unfortunately, most U.S. climates require both heating and cooling during some periods of the year. Although it is relatively straightforward to say that low-solar-gain windows are appropriate in the southern U.S. where air conditioning dominates space-conditioning needs and heating is rarely required, the choice is less clear-cut in the rest of the country. Even in climates where heating is the dominant space-conditioning need, air conditioning is typically needed during some part of the summer. A window that reduces solar gain will lower summer cooling energy consumption but also reduce the solar gains that can significantly offset wintertime heating costs. Thus, all low-e windows will provide less-than-optimal solar gain performance during some portion of the year.

A dynamic window system could optimize a window's solar-gain characteristics according to weather conditions, taking advantage of passive solar effects in winter and rejecting unwanted solar heat gain in summer. The study described in this paper used the energy simulation program DOE2.1 to evaluate the potential benefits of dynamic fenestration systems and compared these hypothetical future systems to what might be the next generation of energy-efficient windows based only on improvements in current technologies—that is, more highly efficient ("ultra") windows with "static" (fixed) rather than dynamic properties. In addition, we considered the impact of combining the properties of the dynamic and ultra windows. Although neither the dynamic nor the ultra windows simulated in this study are currently available, they represent products that could, realistically, result from research during the next decade.

This study also quantifies the impacts of dynamic and ultra static windows in typical residential applications where shading strategies and improved insulation and heating, ventilating, and air-conditioning (HVAC) systems are employed to lower total building energy use. Impacts on peak demand are also examined.

EMERGING TECHNOLOGIES

Technologies currently in research and development are expected to lay the groundwork for the next generation of residential window products. These technologies are described briefly in the following paragraphs (Carmody et al. 2000; Arasteh 1995).

Several technologies are currently being researched to reduce the heat loss (U-factor) of windows. These include vacuum windows, aerogel windows, and improved multi-layer low-e/gas-filled windows. Vacuum windows utilize low-e coatings and an evacuated air space (which virtually eliminates conduction/convection), much like a thermos bottle. Aerogel is a silica-based, open-cell, foam-like material composed of about 4% silica and 96% air; the microscopic cells trap air, maximizing the insulating value, but still allowing light to pass. Multi-layer (two or more low-e coatings and gas-filled insulating gaps) highly insulating windows are currently available as specialty products; new manufacturing approaches (rigid polymeric "nonsealing" inserts, convection baffles, and thin glass) offer the potentials for more cost-effective products.

Technologies to reduce solar heat gain include improvements to existing low-e coatings, light redirecting layers, and self-shading windows. Today's current spectrally selective low-e coatings minimize unwanted solar heat gain by transmitting only the visible light and minimal near-infrared; sharper cutoffs will lead to small decreases in solar heat gain. Lower transmittances across the visible spectrum will reduce solar heat gain further but may also make the glass appear darker. Consideration of frame/glazing shading patterns in window design may also help reduce solar heat gains for high sun angles.

Technologies that enable windows to have dynamic properties include electrochromic glazings, operable shading systems, and light-redirecting devices. Electrochromics are typically multilayer coatings that change transparency over a broad range (from as high as 70% down to a few percent); while researched in the past for commercial building applications, modified electrochromics have significant potentials for use in high-performance residential buildings where seasonal solar switching is needed. Operable and controlled shading systems can be significant energy savers and can be built using currently available technologies. Light-redirecting glazings can be utilized to transmit winter sun but reflect summer sun; such products can take the form of angle selective films, modified coatings, or refractive/reflective glazing geometries.

SIMULATION DESIGN

For this study, the energy performance of dynamic fenestration systems was simulated with RESFEN 5, an interface to the DOE-2.1E energy model (Mitchell et al. 2002). The simulated windows were placed in a single-story, frame-construc-

tion residence with 2,000 ft^2 (186 m^2) of floor area and 75 ft^2 (7 m^2) of window area on each orientation (north, east, south, west). The homes were simulated in eight U.S. cities that represent a range of climates: Boston, MA; Seattle, WA; Denver, CO; Washington, D.C.; Kansas City, MO; Sacramento, CA; Jacksonville, FL; and Phoenix, AZ. Specific levels of insulation were determined for each location based on Model Energy Code standards (CABO 1993), and basement or slab-on-grade construction was chosen in accordance with local practice. Homes were heated with a gas furnace (AFUE[1] = 0.78) and cooled with a 10.0-SEER[2] air-conditioning unit. This set of simulations is referred to as "typical" and is based on past efforts by the National Fenestration Rating Council (Arasteh et. al. 1999). To compare the effects of future high-performance fenestration and the effects of shading strategies for reducing energy, homes with large roof overhangs and deciduous trees were also simulated. Finally, to compare the effects of high-performance windows to the effects of improved insulation and HVAC systems, homes were modeled with approximately doubled insulation levels and improved HVAC system efficiencies, as well as higher-performing windows. Table 1 lists the details of these simulations.

Nine windows were simulated to represent a range of current and potential future window types. The whole-window SHGCs and U-factors for the nine simulated products are listed in Table 2. The first five windows represent a range of currently available fenestration systems: double-glazed windows with clear glass and a wood/vinyl frame (#1) are midrange products, argon-filled low-e windows in a wood/vinyl frame typify higher-performance products on the market today (#2 and #3), and triple-glazed super windows (#4 and #5) represent the most efficient one to two percent of today's market.

The final four windows presented in Table 2 represent a range of next generation products. The dynamic window is assumed to have the heating-season performance of the high-gain super window (#4) and the cooling season performance of the low-gain super window (#5). In other words, it takes the characteristics of today's most efficient windows and adds dynamic properties. We also defined two future high-performance static "ultra windows" that represent further improvements in the energy-efficient characteristics of today's most efficient windows; that is, these future ultra windows have very low U-factors (0.10 Btu/ft^2·h·°F / 0.57 W/m^2·°C), and one has a relatively "high" SHGC of 0.35, while the other a low

SHGC of 0.1. Finally, a window was simulated that combines the properties of the dynamic and ultra windows; it has the heating season properties of the high-gain ultra window and the cooling season performance of the low-gain ultra window.

Products with properties similar to windows #6-#9 are not currently commercially available. The development of windows with electrochromic coatings and automated shading systems is expected to lead to the development of the dynamic properties that windows #6 and #9 have. Windows with U-factors in the range of windows #4 to #6 can currently be achieved with multiple layers, low-e coatings and gas fills, insulating spacers, and frames. Windows with U-factors in the range of windows #7-#9 will require the development of more insulating components and products, as discussed in the "Emerging Technologies" section.

RESFEN was used to calculate several values for the application of each window: whole-house heating energy (Mbtu/GJ), whole-house cooling energy (kWh), primary home HVAC energy consumption[3] (Mbtu/GJ), window heating energy consumption ("energies") (Mbtu/GJ), window cooling energies (kWh), and peak cooling demand (kW). Baseline energies were calculated—HVAC energy consumption not attributable to windows—by subtracting the total annual window HVAC energies from total annual whole-house HVAC energies. Because this value varied slightly from window to window within a city, the value presented here is a numerical average.

SIMULATION RESULTS AND DISCUSSION

Although simulations for all nine windows were performed in all eight cities, all nine windows are not appropriate for each climate. For example, it would not be sensible to install a high-solar-gain window in a Phoenix home. For this reason, only one low-e window (#2 or #3), one super window (#4 or #5), and one ultra window (#7 or #8) is shown for each climate. In heating-dominated climates,[4] such as Washington, D.C., and Kansas City, these windows have high solar gain. In cooling climates and Sacramento, these windows have low solar gain.

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1. AFUE (annualized fuel utilization efficiency) is the amount of heat delivered by a furnace, divided by the latent heat of the fuel the furnace consumes. A furnace with AFUE = 1 is perfectly efficient.

2. SEER (seasonal energy efficiency ratio, expressed in Btu/W) is the cooling output of an air conditioner, divided by the energy input to the air conditioner.

3. We calculated total annual HVAC energy consumption in MBtu by adding heating energy consumption to cooling energy consumption multiplied by the conversion factor for kWh to MBtu (0.003412) and a site-to-source conversion efficiency factor of 3.22. We calculated total annual HVAC energy consumption in GJ by adding heating energy consumption to cooling energy consumption multiplied by the conversion factor for kWh to GJ (0.0036) and a site-to-source conversion efficiency factor of 3.22.

4. For the purposes of this paper, heating-dominated climates are climates in which high-solar-gain super windows use less energy on an annual basis than low-gain super windows. In cooling climates, low-solar-gain super windows use less energy than high-gain super windows. In mixed climates, there is little difference in energy performance between the two types of windows.

TABLE 1
Construction Schemes (Adapted from Mitchell et al. 2002)

Scheme	Characteristics
Typical	*Insulation and building systems:* • 1993 Model Energy Code levels of insulation (described in text) • Gas Furnace AFUE = 0.78; AC SEER = 10.0 *Shading* • Interior shades (seasonal SHGC multiplier, summer value = 0.80, winter value = 0.90) • 1 ft (0.3 m) overhang • a 67% transmitting same-height obstruction 20 ft (6 m) away, intended to represent adjacent buildings • To account for other sources of solar heat gain reduction (insect screens, trees, dirt, building and window self-shading), SHGC multiplier further reduced by 0.1, resulting in a final winter SHGC multiplier of 0.8 and a final summer SHGC multiplier of 0.7
Typical + Overhangs	Same as above, but with 2-ft (0.6 m) overhangs instead of 1-ft (0.3 m) overhangs
Typical + Overhangs + Trees	*Insulation and building systems* • Same as "Typical" *Shading* • Interior shades (seasonal SHGC multiplier, summer value = 0.80, winter value = 0.90) • 2 ft (0.6 m) overhang • A 10 ft (3 m) diameter obstruction 4 ft (1.2 m) above ground level, located 8 ft (2.4 m) away from the house; zero-percent solar transmittance, March 15-Oct. 15; 60% solar transmittance, Oct. 15-March 15 • To account for other sources of solar heat gain reduction (insect screens, trees, dirt, building and window self-shading), SHGC multiplier further reduced by 0.1, resulting in a final winter SHGC multiplier of 0.8 and a final summer SHGC multiplier of 0.7
Double Insulation	*Insulation and Building Systems* • Insulation levels approximately double those of 1993 Model Energy Code standards; locally specific *Shading* • Same as "Typical"
Double Insulation with Efficient HVAC	*Insulation and Shading* • Same as "Double Insulation" *Building Systems* • Simulated ultra efficient systems furnace AFUE = 0.95[*]; AC SEER = 16.0[†]

[*]   The annual energy consumption for AFUE = 0.95 for a furnace was calculated from the energy consumption for the simulated AFUE = 0.78 by multiplying this value by the ratio of the two furnace efficiencies (0.821).
[†]   Estimates of energy savings from higher-rated air-conditioning systems were conservative. SEER measurements are misleading in that air conditioners with a higher rated SEER do not necessarily increase efficiency proportional to the increase in SEER; thus, efficiency improvements for a 16 SEER unit over a 10 SEER unit would be less than 60% (Kavanaugh 2002). The annual energy consumption of a 16 SEER AC unit was calculated by reducing the annual energy consumption of the simulated 10 SEER AC unit by 20%. Peak energy demand for the 16 SEER unit was calculated by multiplying the demand of the simulated 10 SEER unit by 0.943 based on a 6% increase in peak EER found by Kavanaugh (2002).

TABLE 2
Window Types

	Window	U-Factor (Btu/ft^2·h·F)/ (W/m^2·°C)	SHGC
1	Double Clear (static)	0.49 / (2.78)	0.56
2	Low-e, high solar (static)	0.36 / (2.05)	0.53
3	Low-e, low solar (static)	0.34 / (1.93)	0.30
4	Super, high solar (static)	0.18 / (1.02)	0.40
5	Super, low solar (static)	0.18 / (1.02)	0.26
6	Dynamic	0.18 / (1.02)	0.26 or 0.40
7	Ultra, high solar (static)	0.10 / (0.57)	0.35
8	Ultra, low solar (static)	0.10 / (0.57)	0.10
9	Dynamic + Ultra	0.10 / (0.57)	0.10 or 0.35

Glazing systems 2-5 have 90 percent argon gas fill. For all windows, U-factor and SHGC are whole-window values for a 60 x 150-cm generic wood-vinyl frame.
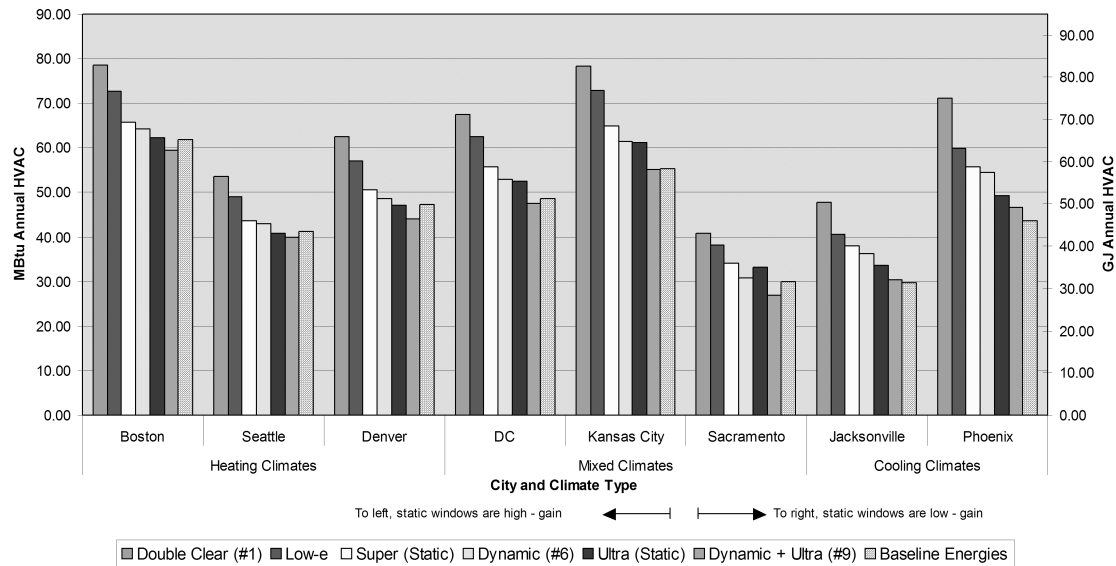
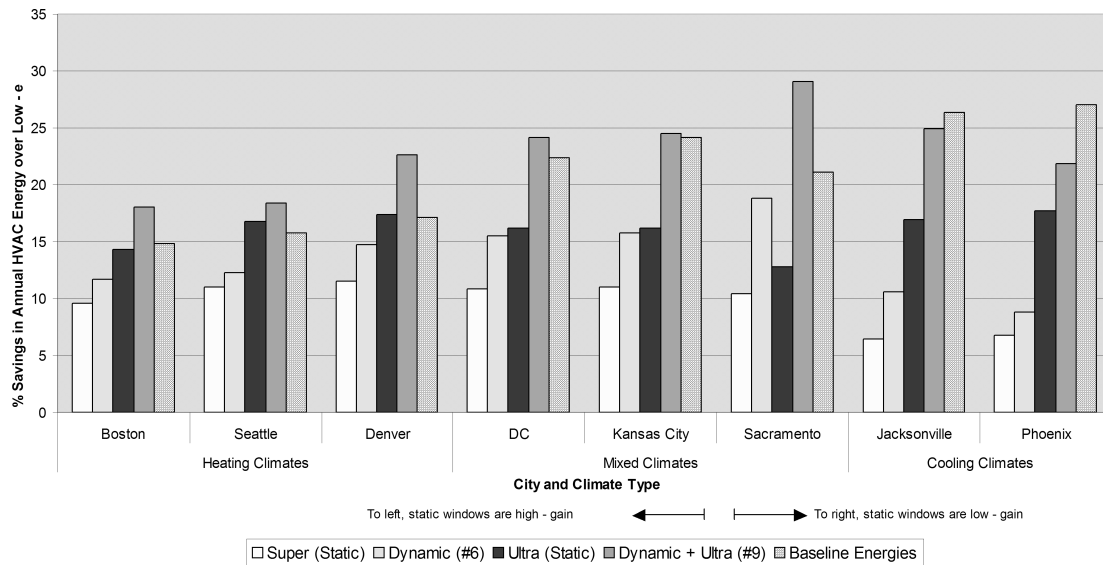***Figure 1*** *Total annual HVAC energy use.*

Figure 2 *Percent of savings in annual whole house energy use over low-e windows.*

Annual Energy Performance Comparisons

As the simulation results in Figure 1 show, homes with low-e windows in most climates used 5 to 10 Mbtu (5-10 GJ) less energy (8% to 15% less total house energy use) for heating and cooling than homes equipped with standard double-glazed windows. As a comparison, baseline energy consumption—the energy consumption that would exist even if the home had no windows—was around 12 to 25 Mbtu (13-26 GJ; 20% to 40% of total house HVAC energy use) lower than energy consumption for homes with double-glazed windows.

Thus, low-e windows typically saved about 40% of the energy use attributable to windows. Simulated homes incorporating the dynamic and the ultra-window technologies studied here can use as little as or less energy than a home with no windows whatsoever; in other words, these future technology advances can convert windows from energy liabilities to energy assets, which will be key in zero-energy construction.

In heating-dominated and mixed climates, homes with super windows (#4 or #5) used 10% to 11% less total house energy than homes equipped with low-e (#2 or #3) windows [see Figure 2]. In cooling-dominated climates, the energy use

of today's super windows was 6% to 7% (of total house energy) lower than low-e windows. In all climates, energy savings from super windows result primarily from the windows' very low U-factor; because cooling climates have a smaller indoor-outdoor temperature differential, the savings from super windows are smaller in these climates.

As Figure 1 shows, energy savings from dynamic windows (#6) were greater than from superwindows, but not always significantly.   In climates like those of Phoenix, Seattle, and Boston, which are all heavily dominated by one season, dynamic windows used only 1% to 2% less total house energy on an annual basis than super windows. However, in mixed climates like that in Sacramento, dynamic windows increase whole house energy savings over low-e windows by another 9%.

Dynamic and static ultra windows were compared in order to assess which technology might be most promising to pursue as the basis for the next generation of highly efficient windows. It was found that in climates with one dominant season, the static ultra windows outperformed dynamic windows. As Figure 2 shows, in heating-dominated climates, homes with ultra windows consumed 14% to 17% less total house energy than homes with today's low-e windows. By contrast, dynamic windows saved 12% to 16%. In cooling-dominated climates, energy savings from ultra windows were significantly greater than those from dynamic windows. However, in Washington, D.C., which is typical of mixed climates, homes with the high-solar-gain ultra window (#4) and the dynamic window consumed roughly similar amounts of energy. In another mixed climate studied—Sacramento— the low-solar-gain ultra window (#6) saved significantly less energy than the dynamic window (12% vs. 14%, respectively). When the sole concern is to minimize annual energy consumption, static ultra windows deliver performance roughly on par with the dynamic window (#6) in mixed climates, slightly superior performance in heating climates, and more significantly superior performance in cooling climates.

Window 9, the "dynamic + ultra" window, represents an outer bound in product design and performance, combining the low U-factors of ultra static windows with the solar-heat-gain properties of the dynamic window. Energy savings from this combined window were 18% to 30% of total house energy use, greater (depending on climate) than the savings from today's low-e windows. As with all the dynamic windows we simulated, the dynamic + ultra window's energy savings were greatest in mixed climates (see Figures 1 and 2). Notably, in heating and mixed climates, homes with dynamic + ultra windows consumed less energy than the baseline "no window" case, turning windows into a net energy benefit for the home.

Peak Demand Performance Comparisons

Figures 3 and 4 show peak cooling energy consumption and demonstrate that windows with low annual energy consumption do not necessarily draw less power during important peak cooling periods. As discussed previously, in heating-dominated and mixed climates, high-solar super windows (#4 in Table 2) performed nearly as well as dynamic windows on an annual energy basis. However, in these climates, with the exception of Sacramento, peak demand savings for the dynamic window (#6) were almost twice as large as savings for a super window (#4). This corresponded to peak power demand in homes with dynamic windows (#6) that was 0.25-0.4 kW lower than the peak power demand for homes with super windows (#4).

In cooling-dominated climates and Sacramento, the trend was different. Since the dynamic window (#6) had the same SHGC as the climate-appropriate super window (#5), the dynamic window offered no additional savings in peak cooling power demand in these climates.

On an annual basis, the high-solar-gain ultra window (#7 in Table 2) consumed less energy than the dynamic window (#6) in heating-dominated and mixed climates. However, the home with the dynamic window had lower peak cooling power demand because of the low summer SHGC for this window. Homes with the ultra window (#7) had cooling power consumption 0.15 to 0.25 kW higher than similar homes with the dynamic window (#6).

In cooling climates, the trend was again different. The low-solar-gain ultra window (#8) used in these climates has a lower SHGC than the dynamic window (#6). Homes in cooling climates with the low-solar-gain ultra window (#8) had peak cooling power demand about 0.3 kW lower than in comparable homes with the dynamic window (#6).

The dynamic + ultra window (#9 in Table 2) offered the deepest reduction in peak cooling power demand in heating-dominated and mixed climates (except Sacramento). Savings were greatest in the most extreme climates and ranged from a 35% to 65% reduction in peak HVAC power demand from homes equipped with the high-gain low-e window (#2). In cooling climates, peak power consumption for window 9 was no lower than that for the low-solar-gain ultra window appropriate for these cities (#8). In all cases, the dynamic + ultra window had very low peak cooling power demand. This demand was only slightly greater (11% to 25%) than that of a home with no windows whatsoever.

Effects of Shading Strategies

Increased shading of windows through the use of large overhangs and trees was found to decrease summer cooling energy consumption and increase winter heating energy
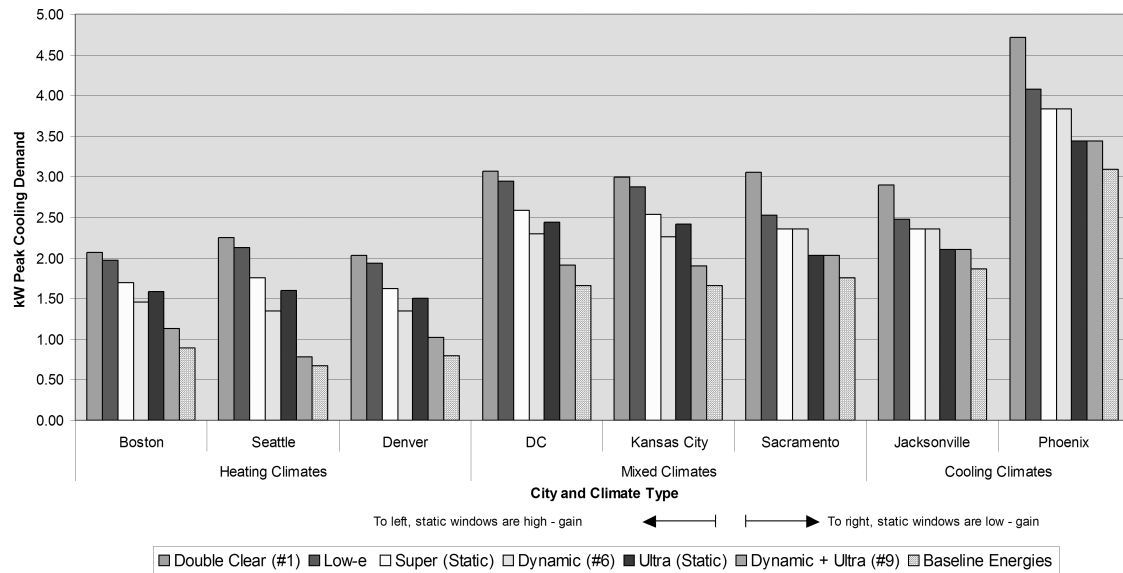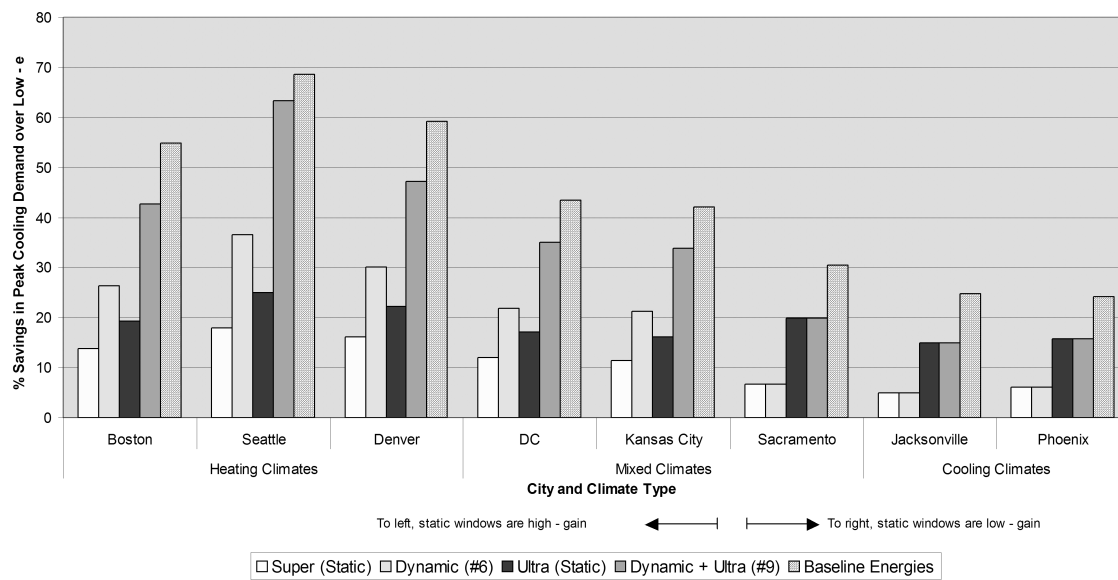
Figure 3 *Peak cooling energy use.*

Figure 4 *Percent of savings in peak cooling load over low-e.*
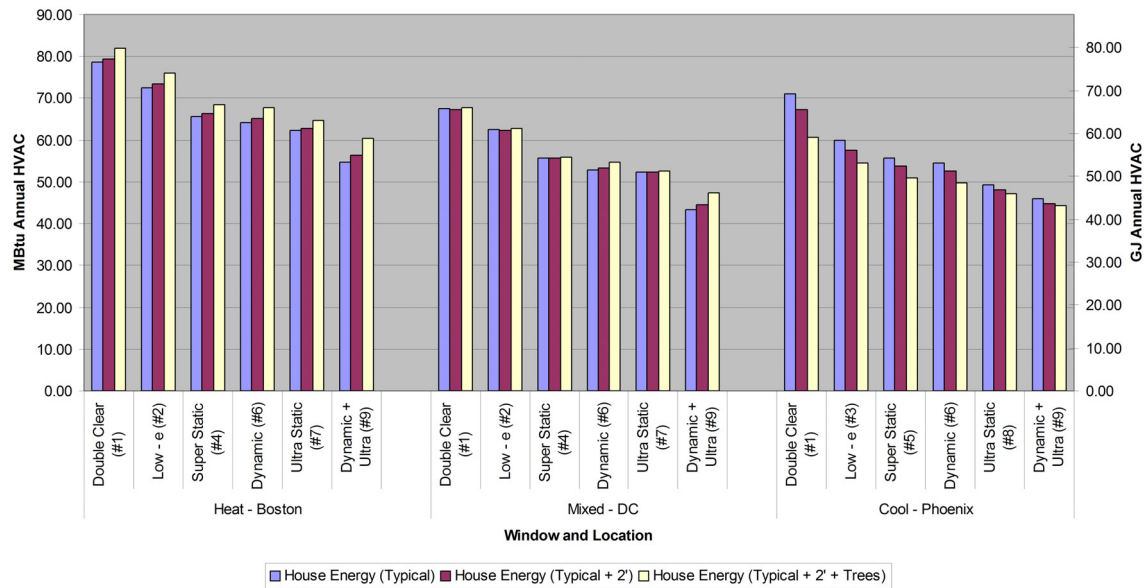
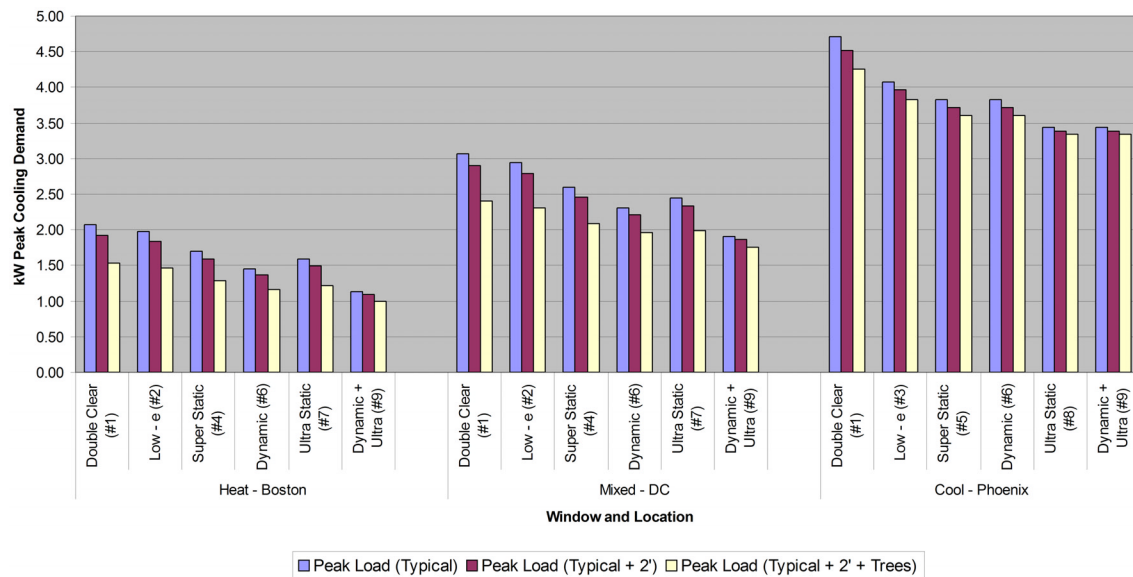**Figure 5** *Annual energy: shading schemes compared.*

Figure 6 *Peak cooling loads: shading schemes compared.*

consumption. Figure 5 shows total annual energy consumption for windows in a heating climate (Boston), a mixed climate (Washington, D.C.), and a cooling climate (Phoenix).

Shading strategies increased annual energy consumption in all heating-dominated cities (not shown) because the resulting increased winter energy use outweighed the summer cooling energy savings. In mixed climates, shading strategies did not significantly affect the performance of static windows, although shading slightly increased the annual energy consumption of dynamic windows.

Shading strategies significantly improved the performance of all windows in cooling-dominated climates. As Figure 5 shows, intelligent use of deciduous trees coupled with a conventional low-solar-gain low-e window (#3) in a climate such as Phoenix can yield savings comparable to those from future window technologies when not shaded. A combination of advanced window technologies and shading led to the greatest possible energy savings.

As Figure 6 shows, deciduous trees were effective in reducing peak cooling demand in all climates. In several heating and mixed climates, tree-surrounded homes with high-
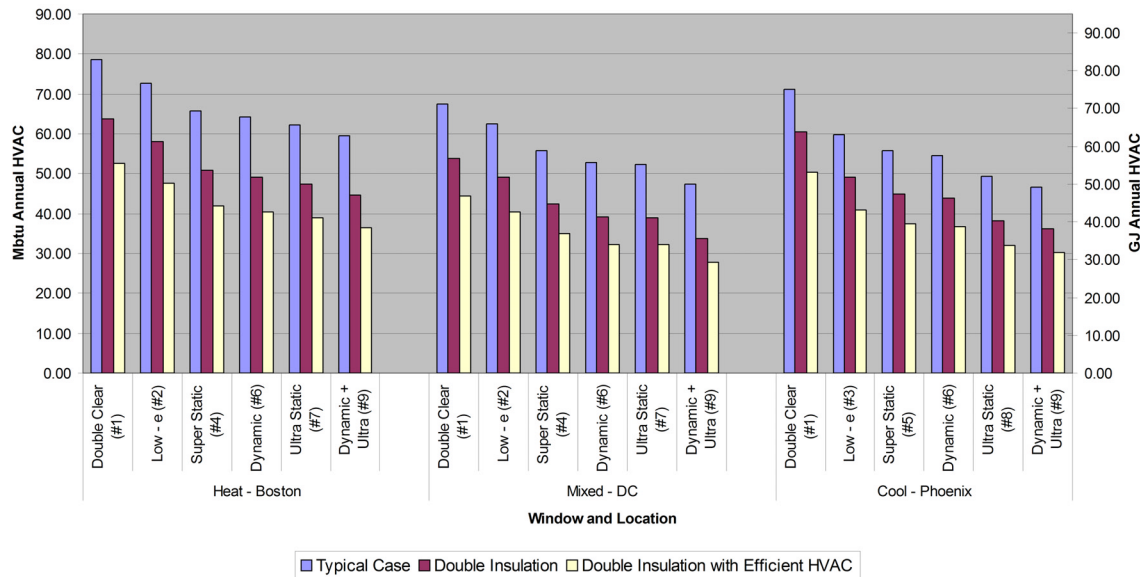
Figure 7 *Total annual HVAC energy use: insulation schemes compared.*
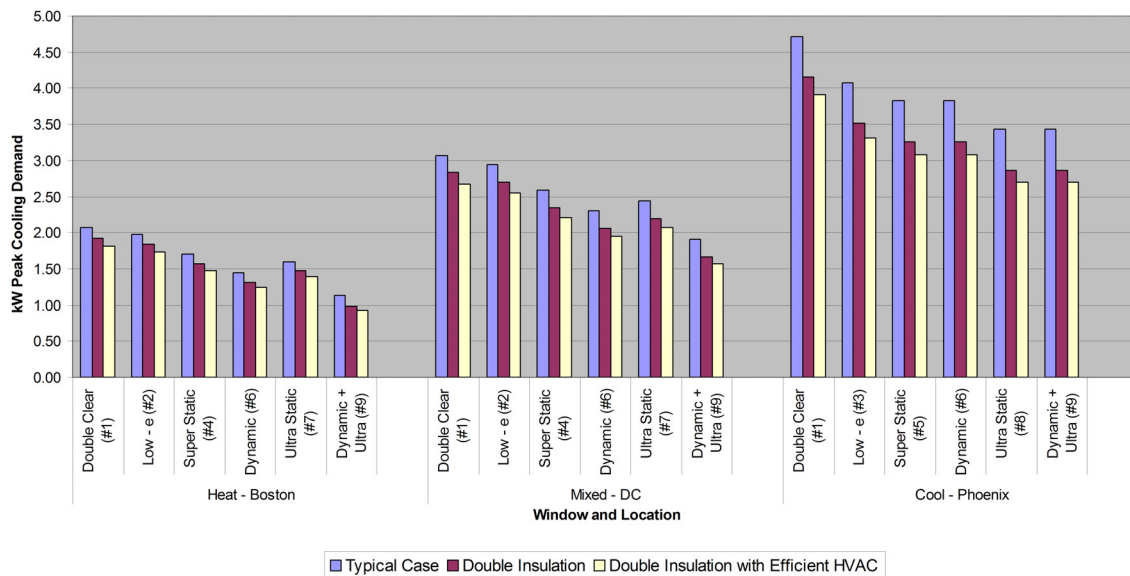

Figure 8 *Peak cooling load: insulation schemes compared.*

solar-gain low-e windows had lower peak cooling than homes with "typical" shading and dynamic windows. In cooling climates, savings were more modest.

In general, in cooling-dominated climates, where shading/overhangs are most effective, advanced window technologies are still required to bring window energy consumption to "zero" levels, although the absolute savings are less. In all climates, shading/overhangs contribute more toward peak reductions than energy reductions.

Effects of Improved Insulation and Building Systems

Doubled home insulation levels were found to dramatically reduce annual home energy consumption, especially when combined with more efficient building systems (Figure 7). Doubling insulation and improving mechanical equipment in a typical home can reduce annual energy consumption up to 37%, depending on climate. In these cases, the impacts of advanced windows are slightly lower in absolute terms but are approximately equal in relative terms. Advanced windows are also a necessity if the energy impacts of windows are to be brought to "zero" levels.

Peak demand savings for the double insulation and double insulation with efficient HVAC cases were not as great as the annual energy savings, as Figure 8 shows. In all climates, doubled insulation and doubled insulation with efficient HVAC helped reduce peak loads, but advanced windows are

the main driver in reducing peak loads. Absolute kW reductions from window strategies are roughly the same in all three cases (base case, doubled insulation, double insulation with efficient HVAC).

SUMMARY AND CONCLUSIONS

We considered three different technology trajectories for future fenestration products:

1. *Dynamic Windows*—Windows with seasonally variable solar heat gain properties to minimize peak summer cooling demand and maximize winter passive solar gain to lower heating costs. These windows would have heat transfer properties similar to those of today's most highly efficient "super" windows ($U_{IP} = 0.18/\ U_{SI} = 1.02$) and have solar heat gain coefficients that varied between the high and low values offered by today's super windows, 0.4 and 0.26, respectively.

2. *Static Ultra Windows*—Windows with significantly lower heat-loss rates ($U_{IP} = 0.10/\ U_{SI} = 0.57$) and fixed solar-heat-gain properties. Two different products were modeled: a high-gain product (SHGC = 0.35) for heating climates, and a low-gain product (SHGC = 0.10) for cooling climates.

3. *Dynamic + Ultra Windows*—Windows combining the properties of dynamic and ultra windows (1 and 2 above); these windows would have dynamic solar-gain control and ultra-low heat-transfer rates ($U_{IP} = 0.10\ /\ U_{SI} = 0.57$) and SHGC varying from 0.35 to 0.10).

Although these products were compared based strictly on performance, other factors will be important in determining which future window technologies are appropriate. These factors include development and production costs, aesthetic appeal, durability, and installation and maintenance. These factors are outside the scope of our simulations, so we did not consider them explicitly. It is important, however, to note that significantly reducing U-factors below current levels and developing dynamic windows will both present technical challenges.

It should be noted that the first dynamic windows on the market will most likely not have the U-factors as low as those noted in this study. Their dynamic ranges will also be different. Such products may be extremely effective in reducing cooling loads and peak demands but may not be as effective in reducing heating loads as well.

The primary conclusion is that the future advanced fenestration products that we studied—dynamic, ultra, and dynamic + ultra windows—offer the potential for significantly greater HVAC energy savings than can be achieved with currently available high-performance windows. Specific conclusions are presented below according to climate type.

Cooling Climates

1. Dynamic window capabilities offer few savings in climates where cooling loads dominate and low SHGCs are the primary drivers of energy efficiency. Compared to high-performance windows with similar U-factors, dynamic windows produce relatively small annual energy savings and no peak cooling demand savings.

2. Future window developments for cooling climates should focus on achieving very low SHGCs (i.e. on static ultra windows) without excessively compromising visible transmittance.

3. Where heating loads are appreciable, dynamic windows can have much lower winter energy costs than static windows with the same U-factors, with no change in summertime peak cooling demand. This decreases results because the difference between summer and winter SHGCs is significant with dynamic windows.

4. Substantial peak and annual energy savings can be realized with large roof overhangs and deciduous trees. Simulations showed that future window technologies with typical shading save more energy than do shading strategies coupled with today's best windows.

Mixed Climates

1. Comparing today's super windows with similar U-factors, dynamic windows achieve significant annual energy savings. Dynamic windows do not require the trade-offs inherent between high-solar windows (heating energy savings) and low-solar windows (cooling and peak demand savings).

2. Static ultra windows use a roughly equal amount of annual energy and significantly more peak energy than dynamic windows. As would be expected, dynamic window technology is a great advantage in mixed climates.

3. In mixed climates, dynamic + ultra windows can save significantly more annual energy than is saved by static ultra windows and can dramatically lower peak energy consumption.

4. Shading strategies have little effect on annual energy consumption for static windows and a slight negative effect on annual energy consumption for dynamic windows. Cooling savings are generally offset by heating energy increases. Use of overhangs or trees lowers peak demand.

Heating Climates

1. Dynamic windows moderately reduce energy consumption on an annual basis and significantly reduce peak demand relative to static windows with the same U-factors.

2. Static ultra windows achieve greater annual energy savings than dynamic windows; however, dynamic windows have significantly lower peak cooling demands. Either technology trajectory—dynamic window or ultra window—could deliver significant improvements in performance.

3. Dynamic + ultra windows significantly reduce annual and peak energy consumption.

4. Tree shading strategies significantly increase annual energy use; however, peak summertime demands are only moderately decreased.

Future Research Paths

Current low-e window technology has led to significant energy savings in typical homes. However, such products are not efficient enough for energy-efficient homes of the future. Higher performing window products need to be developed if windows are not to be an energy drain on the house.

This paper shows there are significant savings to be achieved from both static and dynamic higher performing windows throughout the United States. Dynamic windows (products that modulate solar heat gain on a seasonal basis) are most promising in central and northern climates. Such products provide the best of all worlds: heating energy savings from high-solar windows and cooling and peak demand savings from low-solar windows.

Shading strategies and high-performance HVAC equipment also contribute to decreasing the energy impacts of windows in homes. However, even with shading strategies and high-performance HVAC, there are still significant energy benefits from the higher performing window products studied in this paper. Note that future studies should examine the potential for increased savings from higher levels of shading (i.e., 4 ft (1.2 m) overhangs) and more efficient HVAC equipment (SEER>16), as currently being researched in Building America houses.

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ACKNOWLEDGMENTS

APPENDIX A

How much annual energy use is caused by window performance?

Answer: 3.8 Q (4 EJ) of direct use, about $40B/year; an additional 1 Q (1.05 EJ) of lighting energy could be replaced by daylighting

Background:

From Table 1.1 DOE BTS Core Data Book:
   Residential buildings are 20% of U.S. total of 96.2 quads (101 EJ) or 19.2Q (20.3 EJ)
   Commercial buildings are 16% of U.S. total or 15.4Q (16.2 EJ)

   Windows energy use by end use and building type:
   Residential heating: 2.01Q (2.12 EJ)
   Residential cooling: 0.71Q (0.75 EJ)
   Commercial heating: 0.54Q (0.57 EJ)
   Commercial cooling 0.56Q (0.59 EJ)
   TOTAL = 3.82Q (4.03 EJ) or 4% of US energy use

Note: Lighting accounts for 3.83Q (4.04 EJ) in commercial buildings, so if we assume daylighting has the potential to offset 25% (perimeter and skylights), there is another 0.96Q (1.01 EJ; 1% of total U.S.) windows related energy use.

Assumptions:

- For residential, the percentages of component heating or cooling loads from Table 1.2.10 (i.e., windows are 37% of cooling loads) can be applied to total space heating and total space cooling primary energy from Table 1.2.3. For infiltration, we assume one-fourth of all heating and cooling loads from infiltration are due to windows.
  (Heating: conduction-solar gains is 23%, infiltration is 9%, total = 32%)
  (Cooling: solar gains are 32%, conduction is 1%, infiltration is 4%; total = 37)

- For commercial, the percentages of component heating or cooling loads from Table 1.3.9 can be applied to total space heating and total space cooling primary energy from Table 1.3.3. For infiltration, we assume 15% of all heating and cooling loads from infiltration are due to windows.
  (Heating: conduction-solar gains is 17%, infiltration is 5%; total = 22%)

  (Cooling: solar gains-"free conductive cooling and infiltration" = 31%)

APPENDIX B

Question: What will total energy use attributable to residential windows in the U.S. be if the stock is replaced with low-e windows everywhere?

Frost et al. (1996) estimates that national energy use of residential windows could be reduced by up to 25% if all windows sold between 1994 and 2010 were low-e. This would put much, but not all, of the stock toward low-e.

Frost et al. (1993) estimates that national energy use of residential windows could be reduced by 60% if all windows in the U.S. were replaced (technical potential) with super windows in the north and spectrally selective in the south. Super windows are much better insulators than today's low-e windows.

If all the windows in the U.S. were replaced with low-e, we would estimate energy savings as a percentage of the national total to be between these two bounds. We estimate it to be 40%. Thus, the 2.7 Q (2.85 EJ) drops to 1.6 Q (1.69 EJ).